Lukas Lorenz, Krzysztof Nieweglowski, Klaus-Jürgen Wolter, Karlheinz Bock

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Simulation of bended planar waveguides for optical bus-couplers

Lukas Lorenz*[a], Krzysztof Nieweglowski[a], Klaus-Jürgen Wolter[a], Karlheinz Bock[a]
[a]Electronics Packaging Laboratory, Technische Universität Dresden, Dresden, Germany

ABSTRACT

In our work an optical bus-coupler is proposed, which enables easy bidirectional connection between two waveguides without interrupting the bus using a core-to-core coupling principle. With bended waveguides the coupling ratio can be tuned by adjusting the overlap area of the two cores. In order to ensure large overlap areas at short coupling lengths, the waveguides have rectangular cross sections. To examine the feasibility of this coupling concept a simulation was performed, which is presented in this paper. Due to multimode waveguides, used in short range data communication, a non-sequential ray tracing simulation is reasonable.

Simulations revealed that the bending of the waveguide causes a redistribution of the energy within the core. Small radii push the main energy to the outer region of the core increasing the coupling efficiency. On the other hand, at excessive lowered bend radii additional losses occur (due to a coupling into the cladding), which is why an optimum has to be found. Based on the simulation results it is possible to derive requirements and design rules for the coupling element.

Keywords: optical modeling, optical bus-coupler, non-sequential ray tracing, planar multimode waveguide, waveguide bending, optical simulation

1. INTRODUCTION

The rapidly increasing bandwidth demand in Datacom and Telecom electronics are the main driver for the introduction of optical communication on PCB- and module level [1, 2]. Despite the advantages of optics compared to common used copper wires, optical short range connections are not yet able to replace electrical wiring due to a lack of robust and SMT-compatible technologies for the optical in- and out-coupling from integrated waveguides. Nevertheless, high-performance and cost-effective optical short range connections are needed to meet the future demands in automotive, aerospace or consumer electronics [3].

To open new possibilities, for example in sensor applications for Industry 4.0 or Internet of Things, the integration of optics into structural elements (e.g. car or aircraft components) is emerging. Therefore, the integration of optical fibers in carbon-fiber-reinforced polymers (CFRP) is discussed [4, 5]. To connect these waveguides to sensor modules or the outside world, novel coupling approaches are required, where the waveguide is bidirectional coupled on arbitrary positions without interruption. As a result optical bus systems can be realized where several transceiver modules are connected to the same waveguide (bus). Most state-of-the-art coupling concepts interrupt the waveguide in order to create an access to the bus and use butt coupling approaches for connection to other waveguides or electro-optical converters [6, 7]. Hence, a coupling in real applications is difficult and, if feasible, expensive. Furthermore, it is difficult to connect two or more modules to one single waveguide by a repeater approach to realize a bus system.

The principle of connecting to waveguides by getting their cores into contact has already been investigated on the basis of conventional multimode fibers in [8, 9]. However, with such an approach a bidirectional coupler, which is aimed at in this work, cannot be realized because there are two waveguides used for transmitting and receiving.

In this paper a novel coupling approach is presented, which makes it possible to connect two waveguides without any interruption, which is crucial for the realization of an optical bus-system. Therefore, a flexible and a rigid coupling partner are used, where the cores of the two waveguides get into contact at their upper and lower side faces. By varying the contact pressure it is possible to adjust the coupling ratio because the overlap area between the two cores is changed. Due to that, the flexible waveguide is exposed to a bending with small radius. To relax the alignment tolerances and to maximize the overlap area, multimode waveguides with a rectangular cross section are used. Due to a lack of established results of bended multimode waveguides used for coupling, it is necessary to derive design rules for the described coupling approach by using optical simulation.

*lukas.lorenz@tu-dresden.de

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After briefly introducing the coupling approach in the following section, the development of the simulation model is described in detail. Based on this model, simulation results are presented including bending losses, coupling efficiencies and alignment tolerance analysis.

2. COUPLING CONCEPT

The coupling approach presented in this paper uses an overlap of the cores. Therefore, the coupling partners get into physical contact at their upper respectively lower side face, like it is known in the fiber environment [10]. By getting two cores with the same refractive index into contact without any index interface, there is no total internal reflection (TIR) at that interface any more. Instead, the light is guided in both cores like in a one with increased thickness. The longer the contact length, the higher the amount of modes which are guided in the second core (in addition to the primary core) due to a higher probability of over-coupling of modes of lower order into the second core, as it is shown in Figure 1.

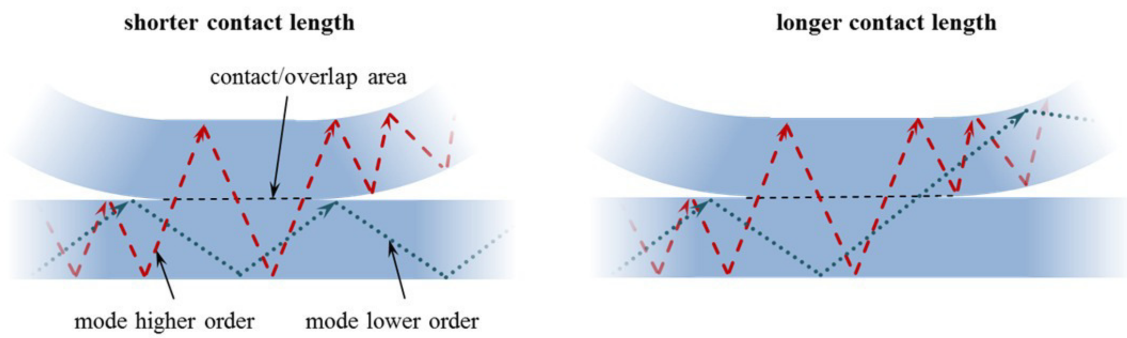

Figure 1. The coupling of two waveguide cores is manly influenced by the contact length due to an increased probability of coupling a mode lower order

Figure 2 shows the adaption of this principle for planar polymer waveguides on board and module level. The first coupling partner, a rigid waveguide, e.g. embedded in CFRP or on an electro-optical printed circuit board, serves as bus-waveguide, while a polymer waveguide on a flexible substrate is the second coupling partner, which could be mounted on an electro-optical sensor module. Both are connected by core-core-coupling, which is why the cladding has to be removed at the coupling point. To ensure arbitrary coupling positions, a foil with adapted refractive index can be used as upper cladding, which can be locally removed for connection.

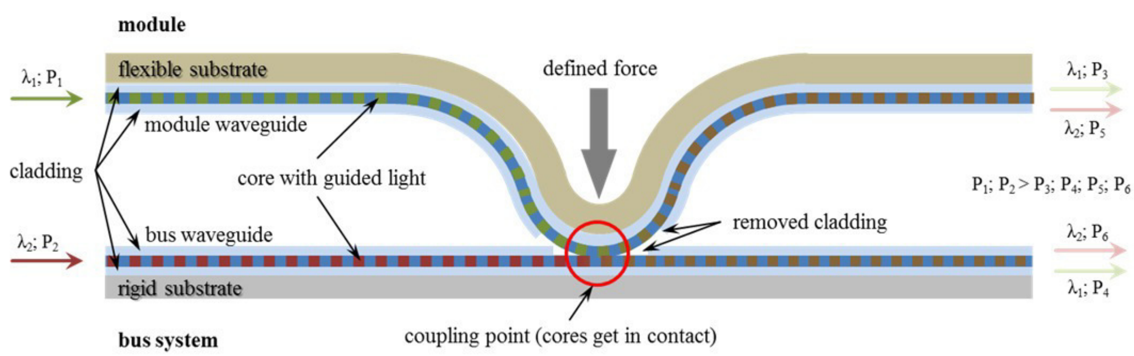

Figure 2. Schema of the bidirectional optical bus-coupler, using a rigid and a flexible waveguide as well as a defined force for the adjusting of the coupling ratio

With the presented approach bidirectional coupling is possible without interrupting the waveguides. While the input signal is coupled into the second waveguide, it still remains in the primary channel for further use and further coupling. Thus, with an adequate optical power budged it is possible to connect several devices to the very same waveguide. Hence, several modules can be controlled by the same signal or the bus waveguide can be used to carry different information e.g. by wavelength division multiplexing, which would reduce the wiring effort enormously. In both cases it might be necessary to use different coupling ratios for the devices. By a defined contact pressure this overlap area can be adjusted, changing the coupling ratio as well. Furthermore, a specific asymmetric coupler is desirable, i.e. different coupling ratios depending on the direction (module to bus or vice versa). A high coupling efficiency for coupling from module to bus is reasonable because the signal is not needed in the module waveguide anymore and should be fully over-coupled into the bus. On the other hand, a connection from bus to module needs a moderate coupling efficiency to keep enough power in the bus for further coupling.

3. FUNDAMENTALS AND MODEL DESIGN

3.1 Selection of the simulation method

The previous section described the requirements and specifications of the coupling element. In order to follow the general design process, as it is shown in Figure 3, a simulation is reasonable before starting any testing to predict the behavior of the device and derive necessary design rules, e.g. the minimum curve radius or suitable overlap areas.

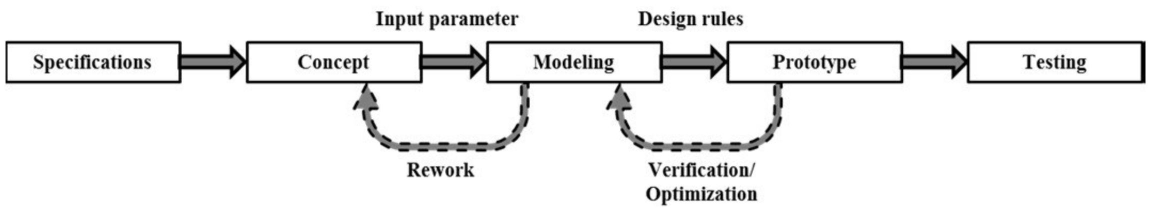

Figure 3. General design process for electronic module development

For the simulation of multimode waveguides two approaches are established: ray tracing and the beam propagation method (BPM) [11, 12]. The main challenge is the great number of modes (up to several thousand) propagating in a multimode waveguide combined with an optical path of several centimeters. Thus, simplifications have to be made. Ray-tracing tools can only calculate the geometrical path of a great number (>100,000) of single rays [13]. Every ray is characterized by its starting point, a direction and a portion of the total power. On their paths the rays are influenced (refracted or reflected) by geometries and refractive indices but not by other rays, which means there are no interferences, i.e. no modes. The disadvantage of this method is that wave-optical effects are not considered. But for geometries (factors) greater than the wavelength it is still a suitable simulation approach. The advantage is a very fast calculation even of complex 3D structures. The elapsed calculating time of an optical multimode waveguide of 4 cm length does not exceed two minutes (with 1 million calculated rays).

In contrast to ray tracing the BPM takes the interferences into account as well [14]. Hence, it is possible to simulate the mode behavior of a waveguide. With several simplifications and numerical approaches the BPM is able to solve the wave equations for static electro-magnetic fields. However, the algorithm works only in straight forward direction, which is why it is not possible to simulate reflections. Even the simulation of bended waveguides is only possible with limitations (bending angle < 45°). Furthermore, the simulation of the aforementioned multimode waveguide would consume more than six hours.

Table 1. Comparison of two simulation approaches for multimode waveguides

Simulation of …	Ray tracing	BPM
Multimode waveguides	+	+
Curves <45°	+	+
Curves >45°	+	-
Back reflection	+	-
Roughness between core and clad	o	+
Evanescence field	-	+
Interference and single mode	-	+
Simulation time for optical paths of several centimeters in 3D	+	- -

Table 1 summarizes the advantages and disadvantages of the two simulation methods. For the proposed coupling approach, which includes waveguide curves, the ray tracing is preferred because of the possibility to simulate greater bending angles. In addition, the time consumption is relevant for the development of complex coupling structures. In this work the commercial ray tracing tool Zemax Optic Studio 15® was used for simulation.

3.2 Development of the ray tracing model

Crucial for reliable simulation results is a solid model basis. Therefore, the design of the model is described in detail in this subsection. In the first step, the waveguide geometry has to be patterned. Because the ray tracing algorithm recalculates a ray at every interface coming across the optical path, it is important to avoid unnecessary surfaces. Especially for bended waveguides this is a challenge, because the tool is approximating most curved surfaces by a finite number of even surfaces (e.g. torus volumes). Hence, there is an undesired out-coupling of light along the bended waveguide. The only curved volumes in Optic Studio® which are calculated without any approximation are spheres and cylinders. That is why the entire geometry was designed with cylinders and rectangles (as mentioned in section 1 the waveguides have rectangular cross sections).

Figure 4 shows the single steps of the model configuration. The cylinders are used to model a 180° waveguide curve. Therefore, the volumes are interlaced and the refractive index of the outer cylinder is overwritten by the index of the next inner one. So it is possible to generate the core with upper and lower cladding. Due to the cylindrical shape, a circular waveguide is formed. With another cylinder and a rectangle (each with the refractive index n = 1) the lower part of the interlaced waveguide cylinders is overwritten. Hence, a 180° semicircle is generated, to which two straight waveguides are added as well as a straight coupling waveguide (all modeled by rectangles). After these steps the geometry model of the coupler is finished.

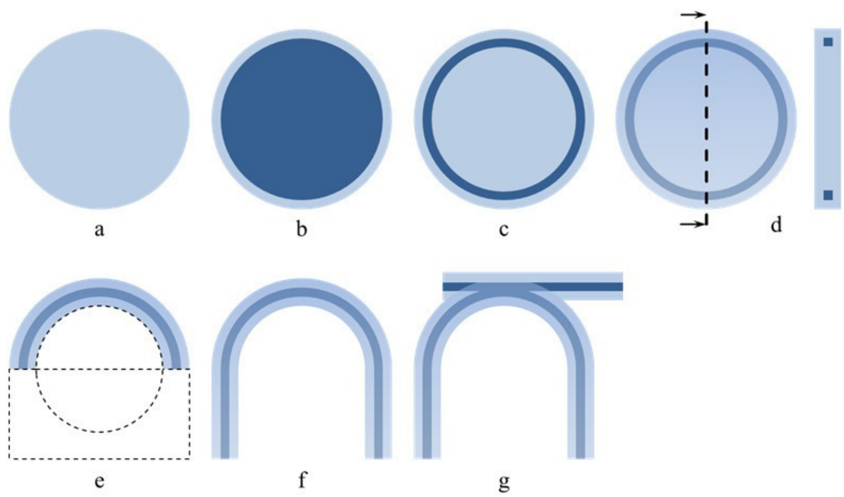

Figure 4. Configuration of the ray tracing model: interlacing the clad-core-clad structure with cylinder volumes (a – c); adding side cladding (d); overwriting several sections with the basic refractive index of air (e); adding input and output waveguides (f); adding the coupling waveguide (g)

The second important aspect for the simulation is the design of the sources as well as the simulation parameters. Choosing a suitable source mainly depends on the application. If the coupler is used in module and board level the waveguides are typically launched by edge emitting lasers or VCSELs. Both have Gaussian beam characteristics with small numerical apertures, which is why a round ($r_s = 5\,\mu$m) Gaussian source with NA = 0.1 is used in the simulation.

For a successful waveguide simulation with ray tracing especially one simulation parameters is essential. The "Maximum Number of Intersections per Ray" defines how often a ray can interact with the same surface [13]. If the ray reaches the maximum number, it will be discarded. In case of a waveguide core the ray hits the side faces several hundred times along a short distance. Hence, it is important to set this number to a maximum. In the presented case 4,000 intersections per ray were allowed.

The complete ray tracing model is shown in Figure 5. It enables simulating two coupling scenarios. First a light coupling from the module side (bended waveguide) to the bus waveguide (straight waveguide) represented by the blue solid arrow. The second scenario is a coupling from the bus to the module represented by the green dashed arrow. Both can be simulated together or separately.

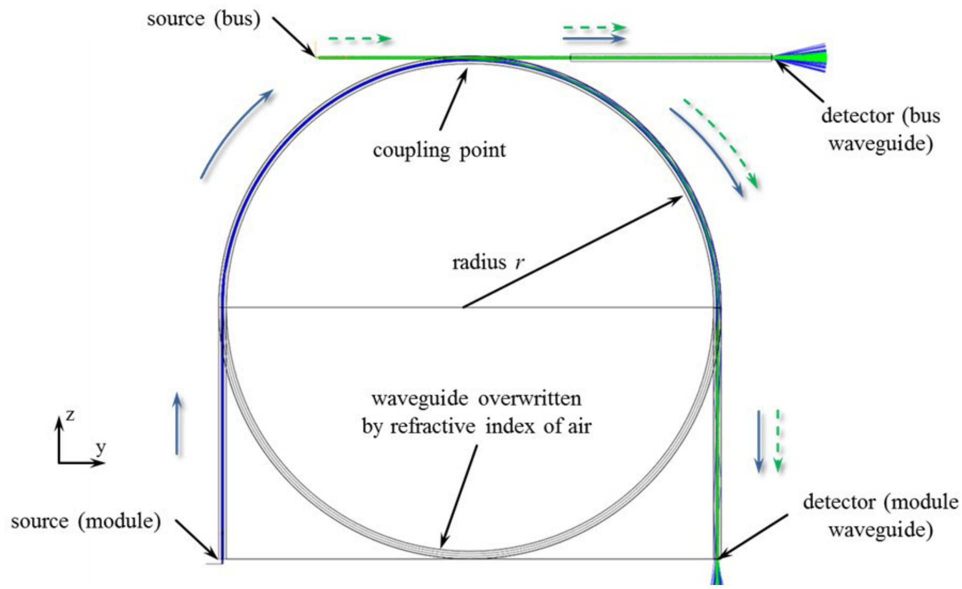

Figure 5. Zemax Optic Studio® model with the optical paths of two different coupling scenarios (solid/dashed arrow)

It should be noted that scattering phenomena are excluded in this work because it is very complex to implement appropriate scattering algorithms into ray tracing tools, especially for scattering due to roughness between core and cladding. Indeed, it can be assumed that scattering has a minor influence due to accurate waveguide manufacturing processes (photolithography), where the surface roughness is $R_a < 20\,\text{nm}$ [15]. Nevertheless, there are methods described in [16] for scattering within ray tracing.

4. SIMULATION RESULTS

4.1 Bending losses and energy distribution

Bending losses occur because rays exceed the critical angle of total internal reflection due to an increased angle of incidence under bending. The first design rule to be determined is the minimum bending radius of the module waveguide. The criteria here is the bending loss a_{bend} which should be $|a_{bend}| < 0.5\,\text{dB}$ which is defined by:

$$a_{bend} = 10\log_{10}\frac{P_{out}}{P_{in}} \tag{1}$$

For the two powers in (1), only the rays guided within the core are taken into account, i.e. the light guided in the cladding is excluded. The model, described in the previous section, is used for the bending analysis without the straight coupling waveguide, so a 180° waveguide bend is simulated. Two detectors were used to measure the input and output power (P_{in} and P_{out}). Furthermore, a space-resolved detector was used at the desired coupling point at the apex of the curve. Hence, the energy distribution within the core can be analyzed.

In Figure 6 the results of the bending loss simulation for different waveguide numerical apertures (NA) are shown. The minimum bending radius is mainly influenced by the NA of the waveguide. To determine a concrete value for the minimum radius, it is necessary to commit to a certain NA. For the proposed coupler a connection to the fiber environment is reasonable which means OM1 62.5/125 with NA = 0.25. Furthermore, with OrmoCore® and OrmoClad® a material system is available for the photolithographic manufacturing of planar waveguides with NA = 0.25. In this case the minimum bending radius is r = 4 mm.

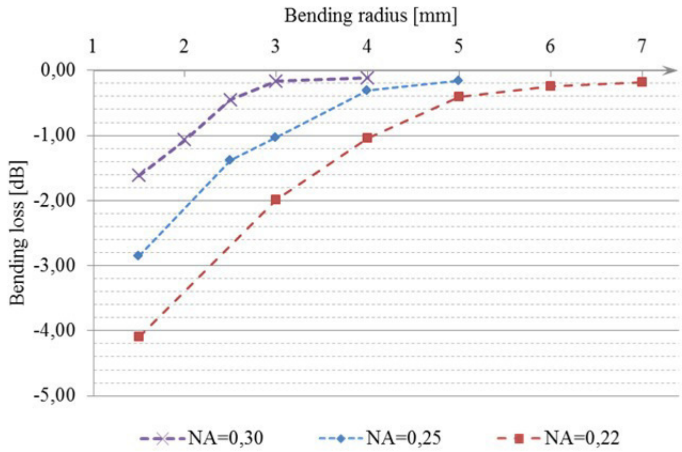

Figure 6. Simulated bending losses related to different numerical apertures

In the second part of the bending simulation the energy distribution within the core is investigated. Figure 7 shows the energy distribution of a straight waveguide and a bended one. It is revealed, that there is energy redistribution due to bending with a maximum at the outer radius of the curve (see Figure 7 b). Due to that, more energy is provided at the coupling position which is located at the outer radius. According to a higher amount of energy, higher coupling rates are expected than with straight waveguides. This is relevant for a specific asymmetric coupler design, where the coupling rate depends on the direction of coupling. The influence of this redistribution is investigated in the next section.

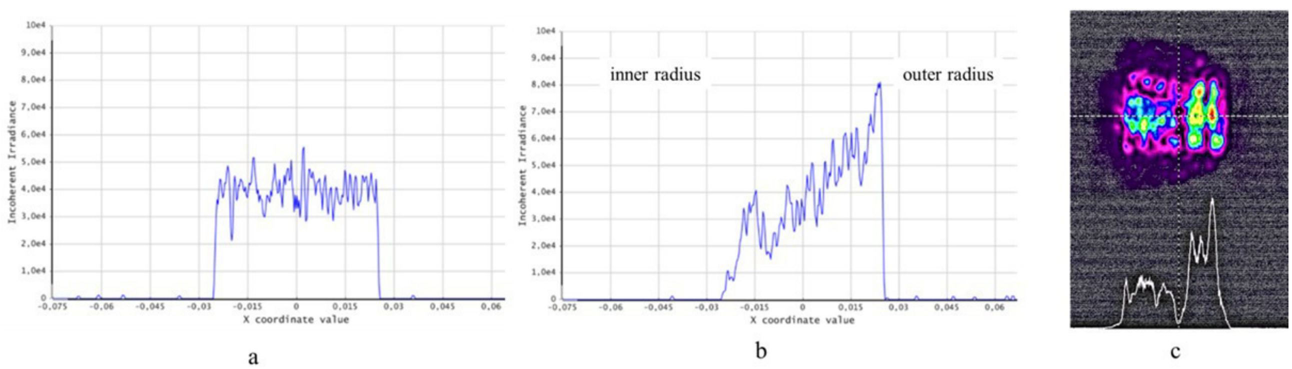

Figure 7. Simulation of the energy distribution of an unbended waveguide (a) and at 5 mm bending radius (b) compared to the measured near field image of a waveguide at a bending radius of 5 mm (c)

4.2 Coupling efficiencies

After the investigation on the bending loss and energy redistribution the consequences for the coupling are analyzed. Therefore, the complete model, described in section 3.2, is used. The key parameter which is studied, is the coupling ratio K, with

$$K = \frac{P_{coupl}}{P_{org}}\,. \qquad (2)$$

In (2) P_{org} is the optical output power of the transmitting channel after the coupling point, i.e. the power remaining in the input waveguide after coupling. On the other side, P_{coupl} is the receiving power which is over-coupled into the second waveguide. Hence, a coupling ratio of $K < 1$ means the majority of the optical power remains in the input waveguide, whereas for $K > 1$ more power is coupled into the second waveguide.

The coupling ratio K is manly influenced by the overlap area of the two waveguide cores, which is defined by the waveguide width and the overlap length *l*, as it is shown in Figure 8. Since the waveguide width is constant, the important parameter to adjust the coupling ratio is *l*. Furthermore, the simulation revealed a connection between the coupling ratio and the radius r of the bended waveguide in case of coupling from module to bus.

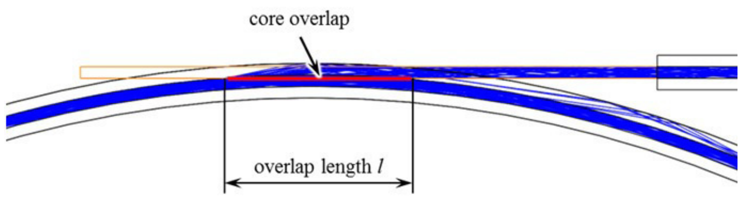

Figure 8. Overlap length between the two cores defining the overlap area (together with the constant core widths)

Figure 9 shows the results of the coupling ratio analysis for the two coupling directions. Two main results can be emerged from this simulation. First, if the light is coupled from the bended waveguide to the straight one, K is influenced by the radius, whereas this is not the case for the opposite coupling direction. This is because the power redistribution within the core (from which the coupling benefits) only occur in curved waveguides (see section 4.1). Due to that, the second important result is revealed: The coupling ratios are differently depending on the coupling direction. For the same coupling length $l = 0.6$ mm ratios of K = 1.60 and K = 0.18 are obtained for module-bus respectively bus-module coupling. Hence, it is possible to realize the aforementioned specific asymmetric coupler design (see section 2). Furthermore, it is possible to make a statement about a reasonable coupling length. For $l = (0.2…1)$ mm the coupling ratio is between K = (0.2…2) and K = (0.05…0.3) respectively, which leaves enough room for different coupling scenarios. To ensure high coupling ratios between module and bus, which might be necessary for some applications, a small bending radius should be chosen.

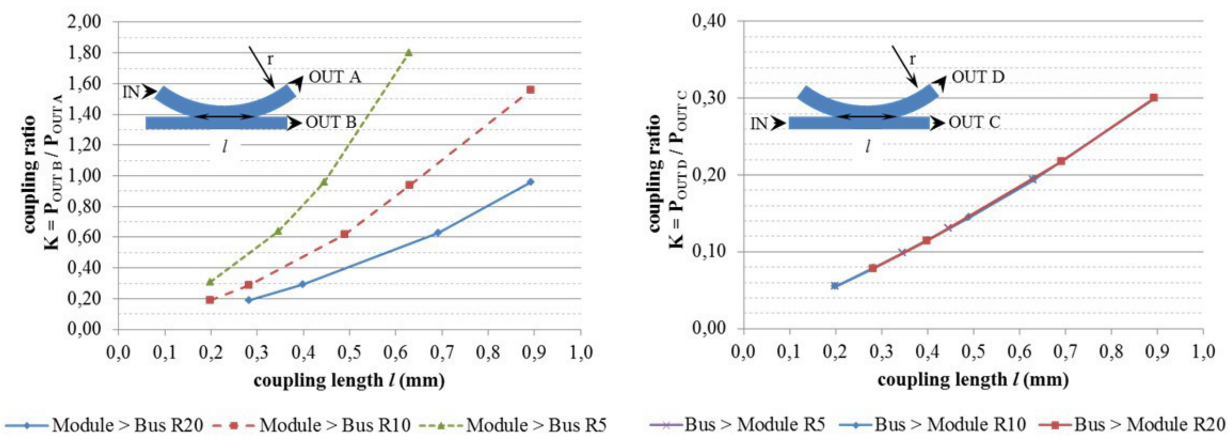

Figure 9. Coupling ratio K of two coupling scenarios related to the coupling length at different bending radii r of the flexible substrate (note the different scales of the diagram axes)

4.3 Tolerance analysis

In addition to the coupling ratios, especially the alignment tolerances are relevant for future applications. The proposed coupling principle benefits from the fact that only one lateral displacement has to be considered. The misalignment along the optical path can be neglected. In the z-axis (height difference between waveguides) the coupling partners are pressed together to adjust the coupling ratio, meaning this displacement can be neglected as well. Hence, the misalignment in the x-axis (transverse to the optical path) is remaining, which can be easily simulated with the ray tracing model. For a reasonable limit for the maximum losses of $|a_x| < 1$ dB, alignment tolerances of $\Delta x = \pm 10\,\mu m$ are determined for a waveguide width of $50\,\mu m$, as it is shown in Figure 10.

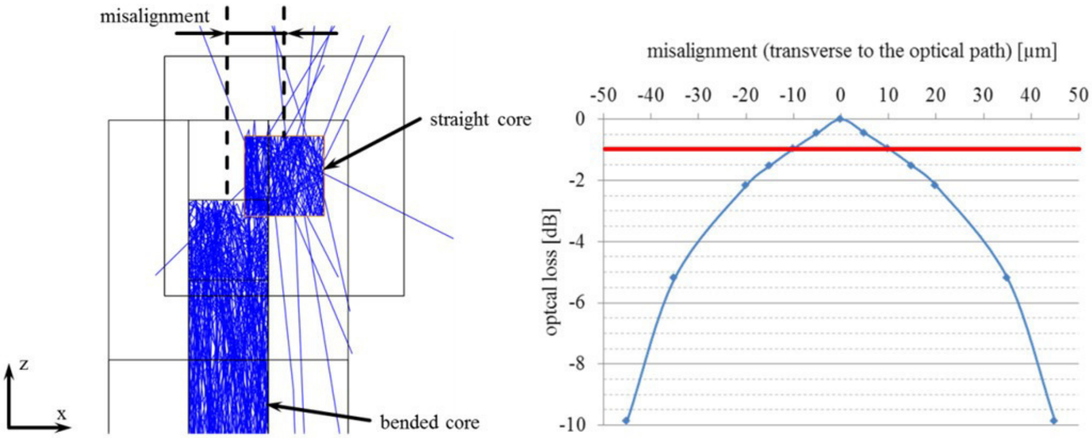

Figure 10. Simulated alignment tolerances in the x-axis for a waveguide width of 50 µm

5. CONCLUSION AND OUTLOOK

The paper proposes a novel coupling approach for a bidirectional optical bus-coupler. The principle enables the connection of several electro-optical modules (e.g. sensor applications) to one bus (e.g. embedded in CFRP) without interrupting the waveguide. For bus communication systems it is desirable to use specific asymmetric coupling principles, i.e. high coupling ratio between module and bus but a moderate one between bus and module. This can be achieved with the presented coupling principle as well.

In order to analyze the coupling approach in detail and derive design rules for future prototypes, a ray tracing simulation was performed. The losses and effects on the energy distribution within the core due to bended waveguides are analyzed. Furthermore, the coupling ratios were simulated related to different bending radii and overlap lengths, as well as the alignment tolerances. From all the simulations the following design rules can be derived:

- bending radius of the flexible waveguide has to be $r \geq 4\,\mathrm{mm}$
- high coupling ratios between module and bus benefit from low bending radii
- range for the coupling length: $l = (0{,}2 \ldots 1)\,\mathrm{mm}$

In future works the overlap length has to be linked to the applied pressure to verify the simulation results with measurement data.

ACKNOWLEDGEMENT

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